AN EXPERIMENTAL INVESTIGATION OF PROTECTIVE FILTERS AGAINST CRACKED CORES OF DAMS

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To

My Parents

CERTIFICATE

This is to certify that the thesis entitled, "An Experimental Investigation of Protective Filters Against Cracked Cores of Dams", by Jyant Kumar is a record of work carried out by him under my supervision and has not been submitted elsewhere for a degree.

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Jyant Kumar

CONTENTS

ABSTRACT

An experimental set-up for conducting No Erosion Filter test in the laboratory has been designed and constructed and a step wise procedure has been evolved.

No Erosion Filter test as proposed by Sherard & Dunnigan (1989), has been demonstrated to give reproducible results for designing filters against cracked core of dams & embankments. Sherard's guidelines for the natural cohesive soils as base materials, have been found to be suitable, whereas Terzaghi & Corps of Engineers' criteria for these soils have been shown to be conservative. For fly ash (both untreated and treated with lime) Sherard's recommendations based on percentage finer than 75 micron only, do not give satisfactory results whereas Terzaghi & Corps of Engineers Criteria give results which are quite close to the experimentally determined values.

It has been investigated that the cylinder dispersion test (Atkinson et al. 1989) is a suitable laboratory method to examine erodibility /dispersibility of soils used for construction of cores of embankments and dams.

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CHAPTER I

INTRODUCTION

There is now general acceptance of the concept of critical filters and of the necessity in filter design to consider explicity the presence of defects such as cracks in the core of an Earth Dam. The importance attached to these filters results from the observations that considerable damage can occur from the insidious progress of internal erosion within the water retaining embankments. By its very nature, this process will be hidden from view and it will generally be difficult to detect until manifested by large scale defects such as the formation of sinkholes. This had happened in case of damage to Balderhead dam in Northern England (Vaughan et.al. 1970).

Cracks in the core may occur due to many reasons, such as differential settlement, drying and shrinkage in arid climate, improper bond between adjacent layers of the core, earthquakes etc. It was found by Sherard (1986) that differential settlement is the main notified cause of cracks in the dam. So due to these identified facts and some practical examples, it is now being accepted that these concentrated leaks can even develop in well design dams/embankments.

Earlier in the literature of Earth & rockfill dams, designers were mainly concerned with the selection of a suitable core material, but now it is accepted that a well designed filter is perhaps the most important element as regards the safety of an earth dam against concentrated leaks through its core.

Pioneering work by Sherard & his associates in recent years has been carried out to evolve laboratory test~~s~~ equipment and procedures for designing successful filters against concentrated leaks through the core of dams/embankments. They have recommended a No Erosion Filter Test (NEF) in designing the protective filters against cracked core of dam.

In the present study, an experimental set up has been designed and fabricated and a detailed step wise procedure has been evolved to create an experimental facility for conducting NEF tests in the laboratory.

Two materials viz. local silt and fly ash (untreated & treated with lime) have been chosen to investigate characteristics of critical filters for embankment cores built from these materials. The experimental results have been compared with the guidelines proposed by Sherard & his associates and also with those available in literature by Terzaghi & Corps of Engineers.

A cylinder dispersion test recently proposed by Atkinson et al. (1990) has been adopted to examine the erodibility/ dispersibility nature of the base materials.

CHAPTER II

LITERATURE REVIEW

2.1 FILTER DESIGN CRITERIA

At present there is a limited literature on designing successful filters against cohesive core material. It is now widely accepted that concentrated leaks can develop in well designed dams. From the very beginning designers had tried to fix some suitable guidelines on the basis of their experiments with filter materials. At that time designers were not assure of the cracking in the dam cores, so they had tried to establish some suitable filter design criteria based on intact condition of the core & very little effort was made to take into account the problems of internal erosion in the dams.

Terzaghi (1948) had recommended filter design guidelines, which are still followed by many peoples. He fixed these guidelines on the basis of his wide experiences with design of dams. The main points of this criterion are as follows:

(i) D_{15} of the filter material should be at least four times the d_{15} of the base material. This concept was introduced so that sufficient amount of head may be lost in the filter material, to keep the seepage forces to minimu

values.

(ii) D_{15} of the filter material should not be more than four times d_{85} of the base material. This concept was introduced to take into account the prevention of passage of fines through filter material.

Terzaghi's criterion has been found to be valid particularly for granular materials. But this simple criterion do not give a unique filter material gradation curve for a particular base soil. As per this criterion, D_{15} of the filter material increases progressively as the width of the gradation curve of the given base soil increases. For any D_{15} of the filter material, the void volume and permeability will decrease as the width of gradation curve of the filter material increases and vice-versa. Sand-gravel filter material that satisfy D^{*}_{15}/d_{15} ratio, may be so widely graded that its permeability would not be much different from that of the base material. This had happened in the case of Teton dam (Seed & Duncan 1973).

Many investigators had tried to improve the Terzaghi's criterion by modifying in such a way, that it yield a more specific gradation. Prominent among these have been Bertram (1940), the US Army Corps of Engineers (1941), the US Bureau of reclamation (1955), Zweck & Davidenkoff (1957), Karpoff (1955) and Leatherwood & Peterson (1954).

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* Capital 'D' refers to filter particles diameter, lower case 'd' to base particles diameter.

The main effect of these modifications over the Terzaghi's criterion, is that it permits the use of widely graded sand-gravel mixtures as filter materials. However, consideration has not been given to the presence of fines in these filter materials. It was found that if a given filter material contains sufficient quanitity of fines passing through 75 micron sieve, then cracking of the filter may create some loose pockets that would eventually permit the passage of fines through filter material.

It was also demonstrated by field experiences that if the filter material is widely graded, then sagregation problems may arise during construction. These sagregations also create loose pockets in the filter material that will eventually permit the passage of fines.

Here are some more criteria as recommended by different authors.

Bertram (1940) had presented the following guidelines in designing filters.

D_{15} of the filter material should neither be more than 9 times d_{15} nor 6 times d_{85} of the base material.

So this criterion had not fixed any lower limit on the filter design. So like Terzaghi, this criterion was also based on the d_{15} and d_{85} of the base material.

US Corps of Engineers (1948) suggested some modifications over the Terzaghi's guidelines while designing the filter. These modifications are as given below:

(i) $$\frac{D_{15} \text{ of the filter material}}{d_{85} \text{ of the base material}} < 5$$

(ii) $$4 < \frac{D_{15} \text{ of the filter material}}{d_{15} \text{ of the base material}} < 20$$

(iii) $$\frac{D_{50} \text{ of the filter material}}{d_{50} \text{ of the base material}} < 25$$

So instead of only D_{15} of the filter material, D_{50} was also introduced in the concept (iii), to take into account both the shape of gradation curve of the core as well as filter material. These guidelines are widely used by many designers.

Leatherwood and Peterson, Jr. (1954) had fixed the following criterion:

(i) $D_{15}/d_{85} < 4.1$

(ii) $D_{50}/d_{50} < 5.3$

So this criterion had also taken to some extent, the shape of the gradation curves of both filter & core material.

Karpoff (1955) had also presented some guidelines, to take into account the shape of gradation curves of both core & filter material. These guidelines are as given below:

(i) **Uniform Filter**

$$5 < D_{50}/d_{50} < 10$$

(ii) **Well Graded Filter**

(a) $12 < D_{50}/d_{50} < 58$

(b) $12 < D_{15}/d_{15} < 40$

(c) The gradation curve of the filter material should be parallel to the gradation curve of the base material.

2.2 FILTER TESTING METHODS

Current practices of the filter design are mainly based on an experimental evaluation of the suitability of a given material as a filter, especially for dam cores constructed with dispersive soils. Erosive/dispersive nature of the soils is also experimentally investigated.

In the following sections, the various testing methods for filter design are reviewed.

2.2.1 Conventional Filter Testing Using High Pressure

Sherard et al. (1984b) made a number of tests by compacting the base material (30 - 60 mm thickness) over compacted sand & sandy-gravel filter. It was found by Sherard that at low pressure generally at about 1.0 kg/cm^2, no filter failure has occurred for even very coarse filter material. The small amount of the water seeping through the base sample had a very little energy. Due to this fine clay or silt particles from the base sample were unable to pass through even very coarse filter material. Sherard et al (1984b) had also found that if during the test, the water pressure was increased in increments of about 0.5 kg/cm^2 to such a value until a concentrated leak of coloured water develop (usually when the pressure was above 1.5 kg/cm^2) then either the eroded base material sealed the filter face & leak stopped (successful filter) or the base material was carried through the filter without any

sealing (unsuccessful filter). In these tests concentrated leaks always developed at high pressure. In tests with successful filter materials, erosion of the base sample was very less and only a small amount of the coloured water passed through the filter before the leak was sealed. In unsuccessful tests, the leak eroded a relatively large hole (5–10 mm in diameter) through the base sample in a few seconds. Tests of this kinds had been used to define the filter boundry for various fine grained soils.

2.2.2 Slot Test

It was shown later on by Sherard et al. (1984b) that a more direct approach obtained the same results by using a test with a preformed slot in the compacted base sample. This particular test was named as a slot test. The main advantages of slot test over the earlier tests (without any preformed slot) are as given below:

(i) By making the slot in the centre of base sample, the concentrated leak could always be located in the centre of the base sample, thus discharging in the central portion of the filter.

(ii) The slot (initial channel for the leak) would have the same dimensions in all tests.

(iii) The thickness of the base sample could be made more as the water was mainly discharging through the slot, instead of discharge through the sample in earlier tests.

For conducting the slot test, a 6.5 in. thick base sample was used against 4 in. thick filter material. The slot was made with

long strip of sheet metal (0.5 in. wide and 0.06 in. in thickness). Sherard et al. (1984b) observed that a surge of dirty water soon emerged with the application of high pressure (4 kg/cm^2). For tests with successful filters, the flow rate rapidly decreased and water had become progressively clear, finally sealing the filter completely or stabilizing at a very small constant flow of clear water. It was generally possible to judge the test results within 2 - 3 minutes. After conducting the test, it was seen that the amount of eroded base soil washed through the filter material, was very small (commonly 10 - 20 gm) and the filter surface was always appeared clean, with seal found in the first few millimeters of the filter material. For unsuccessful tests, the surge of dirty water had continued with no reduction in the flow rate and the test was stopped commonly after a few minutes. At the end of an unsuccessful test, there was commonly an open hole through the base sample, with a diameter of 10-15 mm or larger. For the successful tests, hydrometer measurements of the particles carried through the filter material, generally showed the same particle size distribution as the original material i.e. the material was completely disagggregated by erosion & movement through the filter voids; and there was no significant quantity of aggregated clay particles remaining clinging together.

Results of earlier tests (Sherard et al. 1984b) with longer slot and at lower water pressure (~ 0.14 kg/cm^2) were not

satisfactory due to: (i) Low velocity of flowing water in case of some clays, there was no erosion of the sample and hence the filter was not tested for its suitability; (ii) Generally the walls of the slot slaked immediately and relatively large chunks of compacted clays fell into the water and thus sealed the filter material.

Because of these results, it was concluded that a satisfactory critical filter should be able to withstand a test with high gradients over a short length of the base sample.

After the high pressure slot test was run on a considerable number of different clays & silts, it was investigated that the water was eroding the compacted base sample into its basic particle sizes.

2.2.3 Slurry Test

Observations of the slot test led to consideration of an another type of filter test, in which clay water slurry was used as the base material. Slurry was made by adding water to base material such that water content is about 2.5 times the liquid limit. Slurry was poured on the top of the filter. A deflector was used to prevent erosion of filter surface. Pressure applied was about 4 kg/cm^2 (Sherard et al. 1984b).

The results of these tests were found reproducible. In successful tests, the surface of the slurry abruptly settled a few millimeters and then stopped moving. Small amount of the cloudy water emerged from the bottom and the flow stopped. The test

remained in the equilibrium with the filter face sealed. For unsuccessful tests, all the base slurry was forced through the filter in 2 – 3 seconds and the upper filter surface was left clean.

On the basis of extensive slot and slurry tests, it was shown by Sherard et al. (1984b) that both the tests gave identical results, and as the slurry test required considerably less laboratory effort to perform as compared to slot test, so mainly slurry tests were later carried out. On the basis of these test results for a large number of different clays & silts, the following guidelines were suggested by Sherard et al. (1984b), for determining effective and economical critical filters:

(i) <u>Sandy Silts and Clays</u>

For silts and clays with significant sand content (d_{85} = 0.1 – 0.5 mm), the existing main filter criterion D_{15} filter/d_{85} base ≤ 5 is conservative and reasonable. Plasticity of the base material does not affect the required filters.

(ii) <u>Fine Grained Clays</u>

For fine clays (d_{85} = 0.03 – 0.10 mm), sand or gravelly sand filters with average D_{15} not exceeding about 0.5 mm, existing main criterion is reasonable and conservative. Plasticity or dispersibility of the clay does not affect the gradation needed.

(iii) <u>Fine Grained Silts of Low Cohesion</u>

Fine silts without significant sand content (d_{85} = 0.03 – 0.10 mm) and of low plasticity (plotting below A line and with

liquid limit less than 30%), sand or gravelly sand filters with average D_{15} not exceeding 0.3 mm, are conservative.

(iv) Exceptionally Fine Soils

Clays and silts with d_{85} less than about 0.02 mm, are not very common in nature. For soils in this category, laboratory filter tests are desirable, but a filter with D_{15} of 0.2 mm or smaller is probably conservative.

2.2.4 No Erosion Filter Test (NEF)

Sherard and Dunnigan (1990) had shown that in case of slot and slurry tests, there was a small amount of visible erosion of the base sample in the successful filter. Later in their research program, another test was conducted in which it was possible to define a filter boundry (D_{15b}), at which no visible erosion of the walls of the preformed hole took place during the test. It was investigated that tests with filters slightly coarser than the boundry had visible erosion. Slot & slurry tests were not found to be satisfactory for impervious soils with d_{85} much greater than about 0.1 mm, but NEF tests were found to be suitable for even coarse grained soils. (Sherard & Dunningan 1989).

In the NEF test, the base soil was compacted on the top of the filter in a plastic cylinder (100 mm diameter for fine grained soils and 200 mm diameter for coarse grained soils) at a standard optimum moisture content. Thickness of base sample was kept 25 mm for fine grained soil & 100 mm for coarse grained soils. A hole was made at the centre of the base sample (1.0 mm diameter for

fine grained soils and 5 to 10 mm for coarse grained soils). The pressure applied was 4.2 kg/cm^2. It was also shown (Sherard and Dunnigan 1989) that test results were independent of the pressure as soon as it was high enough to cause the initial erosion of the base sample. As it was found earlier (Sherard et al. 1984a) that D_{15} size of the filter was a good quantitative measure of the pore sizes that prevent soil particles from passing through. It was possible to define a boundry filter (D_{15b}) such that for tests using D_{15} size smaller than D_{15b}, there was no visible increase in the diameter of the initial hole through the base sample. For tests with filters having D_{15} greater than D_{15b}, the initial preformed hole was eroded, and eroded diameter increases as the D_{15} increases.

So it was concluded by Sherard and Dunnigan (1989) that there is a unique filter boundry (D_{15b}) for each base soil. With the NEF test, it was even possible to define this D_{15b} with an accuracy of 0.1 mm.

In order to correlate the D_{15b} with corresponding base material, Sherard & Dunningan (1989) divided the entire range of soils used for impervious sections of embankment dams, into four broad soil groups as given below:

(i) Soil Group I: Fine silts and clays with more than 85% passing through 75 micron sieve.

(ii) Soil Group II: Silty & clayey sands, sandy silts and clays, with 40 - 85% passing through 75 micron sieve.

(iii) Soil Group III: Silty & clayey sands and gravelly sands, with 15% or less passing through 75 micron sieve.

(iv) Soil Group IV: Soil intermediate between Group II and III.

While determining the soil group for gravelly soils, the gravel fraction was ignored.

(i) <u>Fine Silts and Clays (Group I)</u>

Sherard and Dunnigan (1989) had recommended that NEF test for this group was not much different from that of previously used slot test. The main differences were that, base sample in NEF test is shorter 1 in. than 7 in. in slot test, the initial hole was smaller and filter boundary defined differently. The shorter base sample & smaller initial leakage hole allow a reliable judgement of the test as to whether or not erosion of the hole has taken place.

Sherard & Dunnigan had emphasized that within 1 to 4 minutes of application of full pressure (4.2 kg/cm^2), a thin slot existed over the entire base sample. In tests judged to be successful, equilibrium was reached without visible erosion of the initial preformed leakage hole. The seal of the filter was created wholly by the material from this thin slot on the bottom of the base sample. In test with D_{15} larger than D_{15b}, the smaller size soil particles had passed through the filter so that the eroded material from the thin slot on the bottom of the base sample, was not adequate in volume to reduce the velocity through the preformed hole to a nonerosive velocity. The walls of the hole

were eroded and the hole diameter had become larger.

Sherard and Dunnigan concluded that; (i) For tests with filters having $D_{15} > D_{15b}$, the volume of the erosion of initial preformed leakage hole in the base sample, that is needed to seal the filter and reach the equilibrium, is dependent on the diameter and thickness of the base sample tested; (ii) For tests with filters having $D_{15} \leq D_{15b}$, the results are independent of dimensions of the base sample.

It was investigated in their experiments (Sherard & Dunnigan 1989) that D_{15b} determined in these tests, was independent of the erosion resistance of the base soil. From the results of these tests, Sherard and Dunnigan concluded that generally fine grained silts and clays had D_{15b}/d_{85} greater than 8 (usually greater than 9). For silts and clays which are very uniform at the coarser end, with d_{98}/d_{85} less than 2, D_{15b}/d_{85} is smaller and often in the range from 6 - 7.5. This smaller ratio was because of uniform nature of the base soil, with d_{98} not much different from d_{85}. It was also observed for the soils of Group I that D_{15b} was about 0.3 times D_{15B}.

where, D_{15b} = Filter boundary determined from the NEF test.

D_{15B} = Filter boundry determined from the slurry / slot test.

Note: d_{15} refers to the base soil and D_{15} to the filter material.

(ii) <u>Sandy Silts & Clays (Soil Group II)</u>

For the majority of soils, D_{15b} was in the range between 0.7

- 1.0 mm. The NEF test results for this group of soils are found to be different from those obtained with slurry test (Sherard et al. 1984b). Using the slurry test, the criterion $D_{15}/d_{85} \leq 5$ appeared to be conservative, for soils in the range of d_{85} from 0.1 - 0.5 mm. The differences between the results obtained from the two types of tests (i.e. NEF test & slurry test) increased greatly for sandy soils with increasing d_{85} size and D_{15B}. The filter boundry defined by slurry test was corresponding to a large internal erosion of the hole in NEF test.

(iii) <u>Silty and Clayey Sands with Low Fine Contents (Soil Group III)</u>

Some of the highest and longest dams in the world have been constructed with these group III soils. It was seen (Sherard et al. 1989) that in tests with filters having D_{15} smaller than D_{15b} (successful tests), there was essentially no visible erosion of the initial preformed hole and no erosion of the sample bottom. For successful tests, the initial flowing water was usually slightly coloured for a very short time and then the emerging water became clear.

It was concluded by Sherard and Dunnigan (1989) that for the soils of this group, $D_{15b}/d_{85} = 9$ or 10 for materials with angular grains; and $D_{15b}/d_{85} = 7$ to 8 for materials with rounded grains.

(iv) <u>Clayey and Silty Sands (Soil Group IV)</u>

Sherard and Dunnigan had concluded following guidelines for this group:

(a) Tests on the soils with high content of fines (such as 35 - 40%) have results, similar to those of soil group II and D_{15b} was of the order of 0.8 - 1.5 mm and was independent of d_{85} size.

(b) Tests on the soils having low fine contents (such as 15 - 20%) had results similar to those of soil Group III. The filter boundry D_{15b} was roughly 7 - 8 times d_{85}.

(c) For the soils with the intermediate fine contents over the range 15 - 40%, the test results and filter boundry (D_{15b}) vary approximately linearly with the fine content between those of Group II and Group III.

2.2.5 Vaughan & Soares' Guidelines for the Design of Filters for Clay Cores of Dams

Vaughan & Soares (1982) introduced some new guidelines on the basis of their experiences in connection with the damage to Balderhead dam. The clay core of the Balderhead dam in Northern England suffered a partial failures, due to cracking and internal erosion in 1967. At the time of Balderhead dam design, there was generally no agreed method for designing filters for the clay cores. The filter design was based on the gradings used successfully for the filter drain of Selset dam, built from the similar glacial till, two miles away from Balderhead dam in between 1955 and 1960. The filter design confirmed to rules for non-cohesive soils, which were based on the relationship between d_{85} of the base material and D_{15} of the filter material. Numerous tests performed at the Selset dam, had shown that filter remained

satisfactory for the intact core. The risk of cracking was not considered when the filter was designed. It was found that Balderhead filter had operated successfully where the core remained intact, but it had failed to prevent erosion, where cracking had occured. In the case of cracked cohesive cores, the manner in which the Balderhead core behaved had shown that filter design criteria based on tests on intact clay are invalid.

Vaughan & Soares (1982) adopted a new design principle to define a **perfect filter** as one which will retain even the smallest particle that can arise during internal erosion after complete sagregation and unaccompanied by large particles which would allow self filtering to occur. Initially this principle appears to be impractical for clays, since a filter with sufficient fine pores to retain the smallest clay minerals, would itself be so fine grained that it would be cohesive and subjected to cracking in the same way as the core, which it is supposed to protect. Vaughan & Soares also pointed that for a filter to be effective it is necessary for it, to be non cohesive, otherwise it may itself sustain an open flooded crack without collapse and so would fail to protect a cracked core. When the combination of the seepage water and clay chemistry is such that flocculation occurs, as is usually the case, then the finest particles which can arise are clay flocs and a filter should be designed to retain these flocs.

Above concepts seem to be quite conservative in filter design, as it is based on an assessment of the worst case which

can occur, rather than on what is likely to be happened. Irrespective of the erosion resistance of the clay, it presumes that internal erosion will occur. It does not even recognize that the small particles generated by Erosion of the clay may be bigger than floc size nor that complete sagregation (which this criterion assume to occur) is unlikely.

Vaughan & Soares (1982) pointed out that a laboratory test in which a cracked sample is tested against a filter (e.g. NEF test, slot test, slurry test etc.) is likely to show sealing with a filter which is coarser than required to meet the concept of perfect filter. But no safety factor is needed when design is based on the concept of perfect filter. They had also recommended that a filter finer than those often used in dams, is generally required to meet the criteria for a perfect filter.

Vaughan & Soares had recommended the following procedure to design 'perfect filter' for a given base material.

In a tube (2 in. diameter and 18 in. long), a plug of presaturated filter material was compacted at the bottom of the tube and supported on coarse material. The tube was filled with appropriate water. Water was allowed to flow so that a chemical equilibrium between the water and sand was established, and the permeability of filter was measured. Floc size of the clay was measured in a standard hydrometer without any dispersing agent and these sizes of flocs were introduced in a known concentration, on the top of the filter material. The flow rates were monitored and

water coming through the filter was recirculated. If the filter failed, then dirty water came straight through it, there was a slight decrease in apparent permeability and the flow rate then became stable. If the filter retained the clay, then apparent permeability reduced rapidly & continuously and a thin skin of clay formed on the filter surface.

A new concept which was introduced by Vaughan & Soares was the importance of permeability in design of filter. They argued that the filter permeability might provide a better basis for quantifying filter performance than a grading ratio. They proposed the following best fit relationship for the boundry of effective filter on the basis of their experimental results.

$$K = 6.1 \times 10^{-6} d^{1.42}$$

where K is permeability in mt/sec. and d is size of the particle which will just pass through the filter, in millimeters. They also found out that the success or failure of a filter was typically less clear when graded filter rather than uniform filters were tested.

By the principle of perfect filter, designs were carried out for the filters of Cow Green & Epingham Dams (Vaughan & Soares, 1982). It was also found out that floc size increases with the presence of cations in the water upto a certain limit, beyond which floc size remain almost constant.

2.2.6 FURTHER INVESTIGATION ON VAUGHAN AND SOARES' CRITERION

Indraratna et al. (1990) carried out similar tests as prescribed by Vaughan & Soares (1982), by compacting the filter material in a conventional permeameter in several lightly tamped layers above a 1 in. thick uniform fine gravel. The soil suspension was prepared according to the soil & cation concentration as prescribed by Indraratna et al. (1990). Based on the flow rates and water colour, they classified the filters into three different categories:

(i) Effective filters

(ii) Ineffective filters

(iii) Clogging filters

(i) Effective Filters

The filter was able to retain the fine particles by establishing a thin skin of base material trapped at interface. A noticeable drop of the flow rates & permeability was observed.

(ii) Ineffective Filters

Appreciable amount of fine particles either clog the filter completely or get totally washed out in a muddy flow giving rise to highly turbid effluents.

(iii) Clogging Filters

This phenomenon could be detected by rapidly decreasing flow rates which do not stabilize to constant levels with time, but instead diminish monotonically to practically insignificant values.

Based on their experiments, Indraratna et al. (1990) obtained the boundry between the effective and ineffective filter zones for the lateritic residual soil as a core material, by the given expression:

$$K = 6.5 \times 10^{-4} d_{85}^{1.25}$$

where permeability K is in cm/sec. and d_{85} is specific particle size of the base soil gration curve in millimeters.

Goldsworthy (1990) carried out NEF tests with pressure of 1.1 kg/cm^2 instead of 4.2 kg/cm^2 as prescribed by Sherard and Dunnigan (1989). High pressure slurry test was also carried out simultaneously. He finally concluded that in case of tropical residual soils, the critical filters predicted indirectly from its floc size, is larger than that obtained from direct filter tests. This unexpected results is thought to indicate that floc breakdown occurs in direct tests. They also described that this is uncertain that breakdown of flocs will occur and probably would be of little significance in most cases. So the choice of the appropriate test and design methods depends on the core material grading, flocculated if appropriate and an assessment of the possible flow condition in core defects.

2.3 DISPERSIBILITY/ERODIBILITY NATURE

2.3.1 General

Classification tests have been used by different investigators to identify and classify soils with respect to their dispersive/erodibility nature. The Crumb tests, the SCS

Dispersion tests and the Pinhole tests have been used to identify only dispersive clays, and even they are not suitable for all cases. Perry (1976) summarizes the reasons that why these tests are not suitable to identify erosion characteristics of the same soil. A classification chart was proposed by the Bureau of reclamation. This chart was based on the Atterberg limits. But later on, from the failures of many dams (like Hills Creek, Balderhead and Stockton Creek dam) which lie on the range suited for maximum resistance to erosion, have made it clear that this chart alone is not suitable. It was due to the fact that chart did not take into account the important erosion factors such as the chemistry of soil and composition of the pore and eroding fluid.

2.3.2 Critical Shear Stress Introduced by Shields

Shields (1936) defined critical shear stress as the value of stress for zero sediment discharge,that would be obtained by extrapolating a graph of observed erosion rate vs. shear stress. He measured critical shear stress directly,on remoulded and undisturbed samples of the soil, using a rotating cylinder or a flame test. Based on above shear stress criterion, Perry (1976) divided the nature of the soils into three categories:

(i) Erodible Soils: which are having critical shear stress less than or equal to 4 dynes/cm^2.

(ii) Moderately Erodible Soils: which are having critical shear stress between 4-9 dynes/cm^2.

(iii) **Erosion Resistant Soils:** which are having critical shear stress greater than or equal to 9 dynes/cm^2.

The principal difference between dispersive clays & erosion resistant clays, is because of the nature of cations in the pore water. Dispersive clays have a preponderance of sodium, whereas the ordinary clays have a preponderance of calcium & magnesium.

2.3.3 Pinhole Test

Specifically, this test was advised for the purpose of identifying dispersive clays. It was not intended to be used as a quantitative test for measuring the rate of erosion as a function of velocity of water. A hole of 1.0 mm diameter was provided in 25.4 mm thick sample. Final diameter of the hole and the colour of outcoming water would give the idea of dispersiveness of the soils (Sherard, 1976).

2.3.4 SCS Laboratory Dispersion Test (Double Hydrometer Test)

This test has been widely used by US soil conservation service since 1940, although it was never described in general engineering literature. The particle size distribution was first determined by using standard hydrometer test, in which sample was dispersed with strong mechanical agitation and secondly with chemical dispersant. **Percent dispersion is the term which describe the dispersive nature** and it is the ratio of clay size particles in two tests.

2.3.5 Crumb Test

This test is introduced by Emersion (1954). In this test a crumb of soil (1/4 - 3/8 in.) preserved at the natural water content, was dropped into the beaker containing water. The tendency of the clay particles to go into colloidal suspension was observed after 5 - 10 minutes of immersion. Four grades have been classified based on this test, they are:

(i) Grade I : No reaction.

(ii) Grade II : Slight reaction.

(iii) Grade III : Moderate reaction

(iv) Grade IV : Strong reaction.

In the above test, amount of dissolved sodium relative to other salts in the pore water, was the main factor determining whether a clay is dispersive or not.

2.3.6 Cylinder Dispersion Test

This particular test was recently introduced by Atkinson et al. (1990). It is primarily based on the mechanism of internal erosion. If a crack filled with water occurs, then soil surrounding the crack will expand due to presence of water and effective stress will approach to zero. Under above condition, stability of the crack would depend on the true cohesion present in the soil. If the true cohesion is positive then the crack would remain stable. These inter particle forces which make the crack stable, would be very small, in the order of 1 KPa (Atkinson et al. 1990). If the true cohesion has zero value then due to zero

effective stress, grains surrounding the crack would fall down so that crack would gradually enlarged. Soil grains would only wash when flow velocities are large enough to cause erosion. If the true cohesion has negative value, then as soon as effective stress approaches zero, then the soil grains would tend to move away from the crack and they will cause erosion even due to very small values of seepage velocities.

In this test a cylinder of 38 mm diameter and length of 1.5 – 2.5 times diameter, was consolidated at about 70 KPa and then it was lowered in still water. Based on the test results, soil was classified in three different types:

(i) Type C (Non-dispersive and Cohesive): Sample remain unaffected and water colour remained clear.

(ii) Type N (Non-dispersive and Cohesionless) Sample failed into approximately triangular shape very quickly and water remained clear.

(iii) Type D (Dispersive): Sample reduced to a smaller diameter and water became muddy colour.

Atkinson et al. (1990) had shown that test results were affected by pore water chemistry and free water.

From the literature review it is evident that Tarzaghi's and the US Corps of Engineers, filter design criteria are not generally applicable for cohesive soils. The experimental test procedures for filter design against concentrated leaks through cohesive core materials as proposed by Sherard et al (1989) has

been widely accepted and used in the professional practice. In the present study, the critical filter design guidelines as proposed by Sherard and his associates have been checked against experimental data, obtained from NEF tests on compacted cohesive silty clay (dispersive) and a non cohesive fly ash (erosive).

Among the various methods available in the literature to ascertain the erodibility/dispersibility characteristics of core materials, the one proposed by Atkinson et al. (1990) appears to be most promising. The same has been adopted to classify the two test materials in the present investigation.

CHAPTER III

MATERIALS UNDER INVESTIGATION

Materials which were used during present investigation can be divided into two major groups:

1. Base Materials
2. Filter Materials

3.1 BASE MATERIALS

The soils which were compacted during NEF test, for making base samples, are known as base materials. During the present study, three types of base materials were used. They are as follows:

(i) Local Silt

(ii) Untreated Fly Ash

(iii) Fly Ash Treated with Lime

3.1.1 Local Silt

This soil was taken from the IIT Kanpur campus. This is a part of flood plain deposits of river Ganga and covers wide tracts of land in Northern India. These soils are widely used for construction of embankments for roads, railways, canals and water —
waste

disposal ponds. Field experiences with the embankment slopes built with these silty soils suggest that if not covered by proper vegetation, the slopes erode considerably during prolonged exposure to rain water. Furthermore, these silty soils with small fractions of fine sand and clay, exhibit brittle behaviour in compacted state. Repeated failures of embankments storing fly ash slurry coming out of adjoining Thermal Power Plant at Panki near IIT Kanpur Campus, have been observed to be due to internal erosion caused by seeping water.

Given the increased use of these soils for construction of water/slurry retaining ponds, it would be very useful to establish guidelines for the design of filters to arrest failures arising from internal erosion of the embankment. It was with this in view that local silt was selected as one of the base material in this investigation. Here are some of the characteristics of local silt.

(i) Alterberg Limits

Consistency characteristics of local silt vary within wide limits depending on the percentage of clay content. Typical values for campus soil are as under:

- Liquid Limit : 34.0%
- Plastic Limit : 21.1%

(ii) The specific gravity of the given soil is 2.67.

(iii) Particle Size Distribution

Hydrometer and Sieve analysis were carried out in order to evaluate its particle size distribution. The results are shown in Fig. 4, and the relevent gradation parameters are as indicated below:

Clay (< 0.002 mm) = 6%

Silt (0.002 - 0.075 mm) = 71%

Sand (0.075 - 4.75 mm) = 23%

d_{15} = 0.01 mm

d_{85} = 0.11 mm

Cu = 6.57

C_c = 1.01

(iv) Compaction Test

Standard Proctor Test was carried out on the local silt to evaluate its compaction curve. the results are as shown in Fig. 6. Optimum moisture content and maximum dry density (γd max.) values for this soil are 14.2% & 1.93 gm/cm^3 respectively.

Prior to compaction the soil was mixed with water and stored for 24 hours in order to ensure uniform mixing of soil. This procedure was also adopted for compacting local silt samples for NEF test.

3.1.2 Untreated Fly Ash

This is a waste product from Thermal Power Plants and one of the major environmental pollutant. Roughly more than 30 millions

tons of fly ash is produced in India from various thermal power plants and, its safe & economical disposal poses one of the major challenge to engineers.

One of the ways in which fly ash can be used in large quantities, is to adopt it as a construction material for embankments, both for transportation and storage of waste disposal. Efforts are now being made to use fly ash as an embankment material (for fly ash ponds being built at the thermal power plants sites). Given the fact that in its virgin state, fly ash is totally non-cohesive & highly erosive, it would seem necessary to characterize its erodibility characteristics & also suggesting suitable methods of stabilization so as to enable its use in water retaining embankments. Once again, tests on compacted fly ash suggest brittle behaviour (Singh 1989), implying real danger of cracking of the embankments.

With a view to investigate the erodibility characteristics of virgin & stabilized fly ash, and design of suitable filters to ensure safety against concentrated leaks through cracks in the embankments, fly ash was selected as the base material in the present investigation.

Fly ash for the present study was taken from Panki Thermal Power Plant and has following characteristics:

(i) Chemical Composition

The chemical composition of the Panki fly ash based on gravimetric analysis is as given below (Singh 1989):

SiO_2 = 57.6%

Al_2O_3 = 23.9%

Fe_2O_3 = 9.4%

CaO = 0.86%

MgO = 0.44%

SO_3 = 0.45%

loss at 900°C + Carbon = 6.8%

Alkalis = 0.55%

(ii) pH Value of the Panki fly ash was 7.20 (Singh 1989).

(iii) Specific gravity of Panki fly ash was 2.07.

(iv) Permeability without lime = 2.0×10^{-5} cm/sec. (Singh 1989)

Permeability with lime = 2.7×10^{-5} cm/sec. (Singh 1989).

(v) Particle Size Distribution

Hydrometer & Sieve analysis were carried out on the given fly ash to determine its grain size distribution. The results are shown in Fig. 5. The main gradation characteristics are as under:

Clay size fractions = 9%

Silt size fractions = 79%

Sand size fractions = 12%

d_{15} = 0.006 mm

d_{85} = 0.06 mm

$Cu = 6.0$

$C_c = 1.65$

(vi) Compaction Characteristics

Standard Proctor Test was carried out on fly ash in order to evaluate its compaction curve. The results are shown in Fig. 7. Fly ash attains maximum dry density, γd max = 1.27 gm/cm^3 at an optimum moisture content (omc) of 29.2%.

As brought out by Singh (1989), a 3 day mixing period of fly ash with water, was necessary for ensuring reproducible results on fly ash.

3.1.3 Fly Ash Treated with Lime

As fly ash is a fully cohesionless material, so it alone can not be used for water retaining embankments. But it has been found that when lime is mixed with fly ash, its erodibility properties are improved. This improvement depends on the curing period and percentage of lime. It has been found out by Singh (1989) that at a curing temperature of 25^{o}C, the optimum percentage of lime for Panki fly ash is 6%.

Fly ash mixed with 6% lime was also used in the present investigation as a base material and its characteristics are as given below:

(i) Particle Size Distribution

Hydrometer & Sieve analysis were performed on fly ash mixed with 6% lime and stored for 21 days (at 16 ± 3^{o}C during testing

period). The main gradation characteristics of treated fly ash are (Fig. 5):

Clay size fractions = 0%

Silt size fractions = 82%

Sand size fractions = 18%

d_{15} = 0.027 mm

d_{85} = 0.09 mm

C_c = 0.85

C_u = 1.26

(ii) Compaction Test

Standard Proctor Test was carried out on fly ash treated with 6% lime & after storage for 21 days at $16 \pm 3^{o}C$. The results are as shown in Fig. 7. Optimum moisture content and maximum dry density are 30.0% and 1.18 gm/cm^3 respectively.

3.2 FILTER MATERIALS

The basic filter material used for all the tests, was Kalpi Sand. It is natural river sand available from river Kalpi. It is having light reddish colour and has following characteristics:

(i) Particle Size Distribution

Sieve analysis was done on the natural Kalpi sand and results are shown in Fig. 8. The relevent gradation characteristics for this material are:

Clay size fractions = Nil

Silt size fractions = 2%

Sand size fractions = 98%

d_{15} = 0.28 mm

d_{50} = 0.50 mm

C_c = 0.78

C_u = 2.63

(ii) The Specific gravity of the Kalpi sand is 2.66 and its maximum & minimum void ratio values are 0.91 and 0.48 respectively (Shahu 1988).

In addition to base & filter materials, following materials were also used for different purposes.

3.3 SIDE MATERIAL

this material was used for NEF test. During the present study Ganga Sand was used as a side material. It is also a natural river sand, available from the river Ganga. It has following characteristics.

(i) Colour = Grey

(ii) Specific gravity = 2.68

(iii) Particle size distribution

Sieve analysis was done on the Ganga sand and results are shown in the Fig. 8. The main gradation characteristics are as given below:

Clay size fractions = 0%

Silt size fractions = 12%

Sand size fractions = 88%

d_{15} = 0.094 mm

d_{50} = 0.17 mm

C_c = 1.23

C_u = 2.26 mm

(iv) The values of maximum and minimum void ratios are 1.25 and 0.57 respectively (Shahu 1989).

3.4 GRAVELS AND ROAD AGGREGATES

Gravels were used below the filter materials in the NEF test. These material were having sizes varying between 2.0 mm to 8.0 mm. Road aggregates were used above the base sample in NEF test. These were having size varying between 20 mm to 70 mm.

CHAPTER IV

EXPERIMENTAL SETUP AND TESTING PROCEDURE

4.1 NO EROSION FILTER TEST (NEF)

As it is quite clear from the Literature Review that there are many types of tests, which are employed for testing protective filters against cracked core of the dam. As stated by Sherard & Dunnigan (1989) that No Erosion filter test (NEF) gives more suitable results as compared to slot test, slurry test and conventional tests using high pressure. Vaughan & Soares (1982) have recommended their own experimental setup for designing perfect filter. Indraratna et al. (1990), Pinto & Santana (1990), Lafleur (1984), Goldsworthy (1990) etc. have also suggested some different experimental setup with test procedures. Most of the test procedures are based on the pioneering work of Sherard et al. (1984a, b, 1989) and Vaughan & Soares (1982).

4.1.1 Apparatus Set up

The given test setup used in this study (Fig. 1) was similar to Sherard's NEF test setup with some changes.

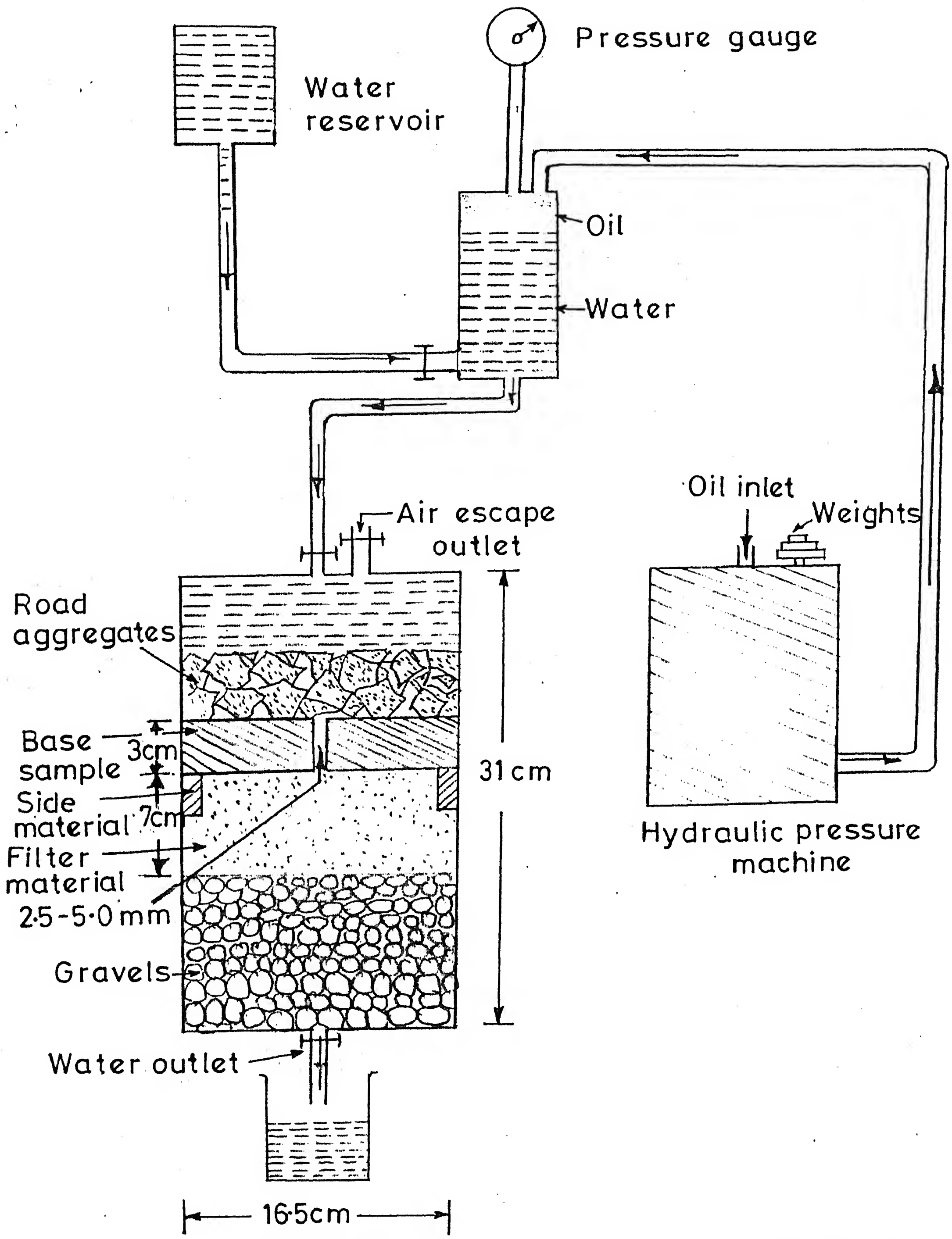

FIG.1 NO EROSION FILTER TEST APPARATUS

The cylinder in which base sample was compacted, was 16.5 cm in diameter (internal). It was made of transparent plastic material and can stand pressure even greater than 12 kg/cm^2, and the total height was 31 cm. The top cap was provided with one pipe connecting to the hydraulic pressure machine & an air outlet. The pressure was applied by means of hydraulic pressure machine. The machine was electrically operated, by using standard grade of hydraulic oil in its reservoir. The continuous pressure could not be applied with this machine, because as soon as the outlet valve was opened during pressure application, pressure was dissipated. Hence the pressure was applied by closing the outlet valve and then again raising the pressure.

4.1.2 Testing Procedure for NEF test

The following procedure was adopted for conducting NEF test, for various base materials used in the present investigation:

(i) The optimum moisture content of the given base soil was determined. For making a compacted base sample of 3.0 cm thickness at maximum dry density (corresponding to optimum moisture content), the given base soil was mixed with calculated amount of water. It was then stored for one day in case of local silt, 3 days in case of fly ash without lime & 21 days in case of fly ash with lime.

(ii) Gravels to be used below filter material were washed properly, so that, when they were submerged in water, the colour

of the water remained clear. These gravels were placed on the bottom of the cylinder as shown in the Fig. 1.

(iii) Filter material of known grading was placed on the gravels, by light tamping by means of tamping rod. Care was taken to avoid any sagregation of filter material.

Side material of known thickness, was also placed as shown in the Fig. 1.

(iv) The given base material as mixed with water, was compacted in 4 layers on the top of the filter surface. The hole was made by pushing a needle/rod (hole was 2.5 mm diameter in case of local silt and 5.0 mm in case of both fly ash with & without lime) into the compacted base sample. A filter paper was placed on the base sample, a hole of exactly same diameter as that of the diameter of the hole, was made in the filter paper. Road aggregates were placed on the top of the base sample very carefully, so that hole was not crushed by aggregates.

(v) The apparatus was assembled carefully and filter material along with gravels, were saturated by raising the water from the bottom, this was to ensure that no air is left, which may otherwise stop or decrease the flow of water.

(vi) *Normal head supply was connected. Discharge and colour of the water were noted. This was repeated 3-4 times. This normal

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* Normal head was a head of 2 meter applied by reservoir of hydraulic pressure machine under gravity.

head supply was disconnected, and full pressure supply was connected (2.5 kg/cm^2 in case of both fly ash with and without lime and 5.0 kg/cm^2 in case of local silt). Colour of the water during application of pressure was observed continuously. The pressure was applied for about 20 - 25 minutes.

(vii) Pressure supply was disconnected and normal head supply was again connected. Discharge and the colour of water were again noted for 3-4 times. If the discharge was significantly decreased then the appapratus was dismantled, or otherwise pressure was again applied for 15 - 20 minutes and discharge and colour of the water were again noted under the normal head, and then apparatus was finally dismantled.

(viii) The final diameter of the hole was observed very carefully. Erosion channels if any, were also examined on the bottom of the base sample.

4.1.3 Classification of NEF tests

The following points based on the NEF test results, will make difference between successful and unsuccessful filter materials for the given base material:

(i) If the colour of water in the very beginning comes dirty either under the normal head or during pressure application, and if it remains dirty for 4 - 6 minutes, then given material is an unsuccessful filter for the given base material.

(ii) If the colour of water comes dirty for about 50 - 60

seconds, either during the normal head or during pressure application and if then it becomes clear, the material may be still successful as a filter for the given base material, depending on the final diameter of the hole i.e. if the final diameter of the hole is increased then material is unsuccessful as a filter or if the final diameter is approximately same then material is successful as a filter for the given base material.

(iii) If the colour of the water remains clear throughout testing period, then still material may be unsuccessful as a filter for the given base material, depending on the final diameter of the hole after completion of test. If the final diameter has been increased then material is unsuccessful as a filter or if it remains unchanged then, material is successful as the filter for the given base material.

4.2 CYLINDER DISPERSION TEST

As seen from the literature review that there is a number of different types of tests carried out for examining erodibility / dispersibility of the given soil. If it is accepted that internal erosion is caused by the absence of true cohesion, then Crumb Test & Pinhole Test, would have deficiences because in these tests, there is no surity whether samples would remain saturated. The samples would be influenced by suction which can give them substantial effective stress even after exposure to free water. In the case of SCS test, it was quite difficult to examine the influence of pore & free water.

In the present study, in order to examine the erodibility / dispersibility of the given soil, the Cylinder Dispersion Test as proposed by Atkinson et al. (1990), was used.

4.2.1 Apparatus Setup

The given test setup is shown in Fig. 2.

The tubes in which slurry is poured in order to make the sample were having 38 mm diameter with a length of about 225 mm. Weights were placed on the disc connecting to the sampling rod as shown in Fig. 2. Perforated discs were used both on the top and bottom of the tubes, in order to drain the water from sample.

4.2.2 Testing Procedure

A sample of the given soil to be tested, was dried and ground to powder. It was then remixed with tap water (i.e. water available from municiple water supply used for drinking and washing purposes). Enough water was mixed to the soil so as to make easy pouring of slurry into the tubes.

After making the slurry, it was poured very carefully into the tubes so as to prevent any presence of air bubbles in the slurry. Enough quantity of slurry was poured so that after consolidation, the length of the sample was exactly twice its diameter. Loading rod with a perforated disc was lowered in the tube. A rubber pipe having its one end in a beaker containing water and other end was connected to the drainage outlet from the tube as shown in Fig. 2. When the slurry was sufficiently strong

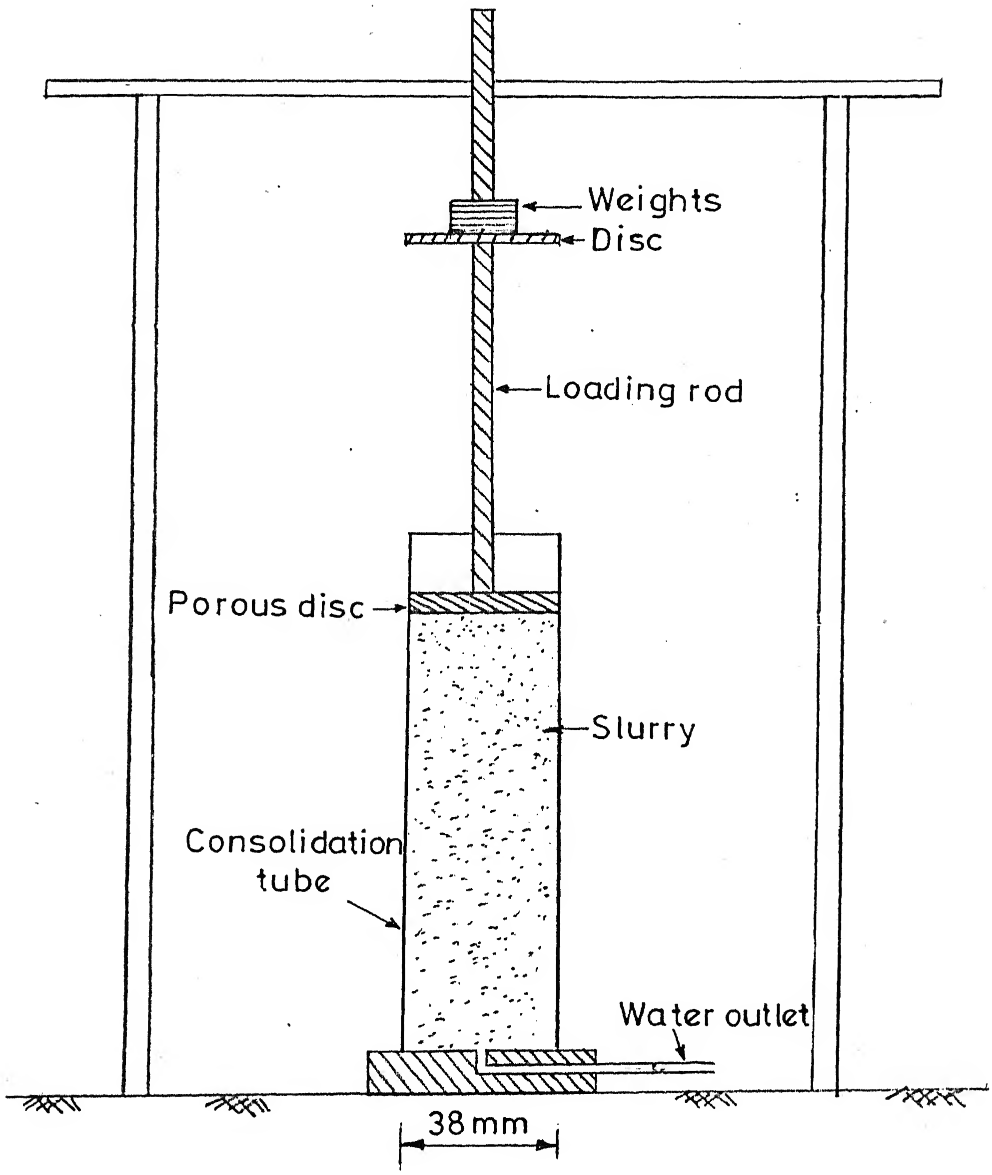


FIG. 2 CYLINDER DISPERSION TEST APPARATUS

to prevent the squeezing of the material around the perforated disc, weights were placed gradually on the loading rod. A consolidation pressure of 1.0 kg/cm^2 was thus applied by these weights. The consolidation pressure was maintained for 2 days on local silt and fly ash without lime, and 2, 7, 14 and 21 days respectively for fly ash with lime. After this time period, the weights were removed and loading rod was taken out from the tube very slowly. The sample was then extruded carefully from the tube and it was cut to exact length, by placing on a sampler. The sample was gently lowered into appropriate water (in the present study both distilled and tap waters were used). After immersion in free water, the sample was observed for 3 days and the behaviour was classified as would be explained below.

4.2.3 Classification of Behaviour

When saturated soil samples were submerged in the given water, one of these three basic characteristic types of behaviour, was observed. These are as follows:

(i) Type C

(ii) Type N

(iii) Type D

(i) Type C: The behaviour was classified as Type C, for the given soils having positive true cohesion. The sample remained unaffected by presence of free water (Fig. 3a).

(ii) Type N: the behaviour was classified as type N for the soils

having cohesion zero (cohesionless). The sample debris would take the form of triangle or as shown in the Fig. 3b.

(iii) Type D: The soil was known to exhibit type D behaviour, for which water becomes dirty and debris of the sample slowly depositing on the beaker surface. The shape of the settled debris was difficult to identify it is as shown in Fig. 3c. The final water colour was dirty even after 2-3 days.

All above behaviour classifications were same as proposed by Atkinson et al. (1990).

CHAPTER V

TEST RESULTS

No Erosion filter tests (NEF) and cylinder dispersion tests were carried out on local silt and both fly ash untreated & treated with lime as base materials. The complete picture of results as obtained from these tests are as given below:

5.1 LOCAL SILT

5.1.1 Cylinder Dispersion Test

The behaviour of local silt sample was observed both in distilled and tap water. The following results were obtained.

(A) Behaviour of the sample in distilled water

When the sample was gently lowered in the beaker containing distilled water, the water became slightly turbid. Sample was standing vertical and after about 3-6 minutes, dispersion rate increased and cracks were appearing near the bottom of the sample and water was becoming more turbid with the passage of time. After 35-37 minutes, the colour of water was so turbid that sample had become invisible through the walls of the beaker. Observations were continued for 24 hrs. and there was not much

change except for slight reduction in the turbidity (due to settlement of coarser particles).

The test was repeated on four samples, and in each case similar behaviour was observed.

According to Atkinson et.al. (1990) local silt exhibits Type-D behaviour in distilled water.

(B) **Behaviour of the sample in tap water:**

Four samples were submerged in tap water and the observed behaviour of local silt was almost similar to that earlier when distilled water was used, except that sample became invisible in 40-42 minutes, instead of 35-37 minutes. The rate of dispersion of local silt sample in tap water was slightly less as compared to that in the distilled water.

Thus local silt also exhibits Type D behaviour in tap water.

5.1.2 NEF Test for Local Silt as a Base Material

A number of NEF tests were conducted on the local silt, by using different gradings of filters materials. The results are as follows:

(A) **Filter material having D_{15} = 0.28 mm (gradation curve 1 of Fig. 5)**

Number of tests conducted by using this filter material was two and in each test almost similar results were obtained.

Initial discharge under the normal head had varied between 2.126×10^{-2} - 2.338×10^{-2} ml/sec.-cm^2 Pressure of 5 kg/cm^2 was

applied for 20-25 minutes, the water still remained clear. Discharge was again measured under normal head, it varied between 0.974×10^{-2} - 1.057×10^{-2} ml/sec.-cm^2, the water was again clear.

After conducting the test, it was seen that there was no increase in diameter of the hole and by observing the bottom of the base sample, it was found that erosion channels were formed on the surface of the sample.

Thus the material having D_{15} = 0.28 mm, is a successful filter for local silt as a base material.

(B) Filter material having D_{15} = 0.6 mm (gradation curve 2 of Fig. 4):

With this filter material two tests were conducted and following results were found:

Initial discharge under the normal head had varied between 2.338×10^{-2} - 2.598×10^{-2} ml/sec.-cm^2 and water was clear. Full pressure of 5 kg/cm^2, was applied for 23-28 minutes. It was found that water was coming turbid for the first 40-70 seconds and then it became clear. Discharge measured under the normal head, varied between 1.046×10^{-2} - 1.231×10^{-2} ml/sec.- cm^2.

The final diameter of the hole after completion of test remained almost same and erosions channels were present at the bottom of the base sample.

Thus the material having D_{15} = 0.6 mm, is also a successful filter for local silt as a base material.

(C) Filter material having D_{15} = 0.7 mm (gradation curve 3 of Fig. 4)

Three tests were conducted with this filter material and following results were found.

Initial discharge under the normal head in this case varied between $2.338 \times 10^{-2} - 2.923 \times 10^{-2}$ ml/sec.- cm^2 and water was coming clear. Pressure of 5.0 Kg/cm^2 was applied for 22-35 minutes, water was coming turbid for the first 10-12 minutes and then it became clear. Discharge measured under the normal head, varied between $1.299 \times 10^{-2} - 1.070 \times 10^{-2}$ ml/sec.-cm^2 and water remained clear.

Final diameter of the hole after completion of test, had increased to 4-5 mm and erosion channels on the bottom of the base sample, were present.

So these results indicate that material having D_{15} = 0.7 mm, is an unsuccessful filter material for the local silt as a base material.

<u>Filter boundry (D_{15b}) for local silt</u>

It is clear from the test results of these three filter materials that D_{15b} = 0.6 mm for local silt as a base material.

5.2 UNTREATED FLY ASH

5.2.1 Cylinder Dispersion Test

Untreated fly ash samples were tested both in distilled and tap water. Following results were noted:

(A) **Behaviour of the sample in distilled water**

When the sample was gently lowered in the beaker containing distilled water, the colour of the water was soon becoming backish. After 1-2 minutes, cracks were appearing on the surface of the sample, starting from its bottom. After 5-7 minutes, the sample had collapsed due to widening of cracks and water became more blackish. Slowly with the passage of time, the water was becoming clear and after about 80-100 minutes, it had become absolutely clear. The debris from the sample has deposited at the bottom all around a small central portion of the sample as shown in Fig. 3b.

According to Atkinson et al. (1990) untreated fly ash exhibits Type N behaviour in distilled water.

Tests were repeated on three more samples in distilled water and similar behaviour was observed.

(B) **Behaviour of the sample in tap water**

With the help of four tests conducted on fly ash samples in tap water, it was found that there was no difference in the behaviour (Type N) of fly ash samples in tap water as compared to those tested in distilled water. The time of collapse had also remained the same.

5.2.2 NEF Test for Untreated Fly Ash as a Base Material:

In this case three different filter materials were used for fly ash as a base material. The test results are as follows:

(A) Filter material having D_{15} = 0.54 mm (gradation curve 3 of Fig. 5)

Three tests were conducted by using this filter material and each one has contributed almost similar result as given below.

Initial discharge under the normal head had varied between 2.033×10^{-2} – 2.338×10^{-2} ml/sec.–cm^2 and the colour of water was blackish. Pressure of 2.5 kg/cm^2 was applied for 12 – 16 minutes, water colour was still blackish. Subsequent discharge under normal head varied between 1.559×10^{-2} – 1.670×10^{-2} ml/sec.cm^2 and the colour of water was still dark. Examination of black colour of water indicated presence of fine fly ash particles escaping through the filter material.

The final diameter of the hole had increased to 6 – 8 mm and erosion channels on the bottom of the sample surface were present.

These results indicate that material having D_{15} = 0.54 mm, is an unsuccessful filter for untreated fly ash as a base material.

(B) Filter material having D_{15} = 0.43 mm (gradation curve 2 of Fig. 5)

Three tests were conducted with this filter material for untreated fly ash as a base material, and following results were obtained.

Initial discharge under the normal head had varied between 1.999×10^{-2} – 2.165×10^{-2} ml/sec. cm^2 and water colour was blackish. Pressure of 0.5 kg/cm^2 was applied for 14 – 18 minutes;

water was coming clear. Discharge noted under normal head had varied between $1.314 \times 10^{-2} - 1.461 \times 10^{-2}$ ml/sec.cm^2, the water was quite clear.

The final diameter of the hole after conducting the test, had increased to 6 - 7.5 mm and erosion channels were also present on the bottom surface of the base sample. So this material is too an unsuccessful filter for fly ash as a base material.

(C) Filter material having D_{15} = 0.28 mm (gradation curve 1 of Fig. 5):

Three tests were conducted by using this filter material for untreated fly ash as a base material and following results were found.

Initial discharge under the normal head had varied between $1.799 \times 10^{-2} - 1.999 \times 10^{-2}$ ml/sec.-cm^2 and water was clear. Pressure of 2.5 kg/cm^2 was applied for 15-17 minutes; water remained clear. Discharge measured under the normal head varied between $1.114 \times 10^{-2} - 1.231 \times 10^{-2}$ ml/sec.-cm^2 and water was again clean.

Pressure of 2.5 kg/cm^2 was again applied for 13-16 minutes and discharge under the normal head was measured again, it varied between $1.063 \times 10^{-2} - 1.169 \times 10^{-2}$ ml/sec.cm^2 and water was still coming quite clear.

Thus above results indicate that this material (D_{15} = 0.28 mm) is a successful filter for untreated fly ash as a base material.

Filter boundry (D_{15b}) for Untreated Fly Ash

Based upon the above test results, it may be recommended that those materials having D_{15} above 0.28 mm, are unsuccessful filters for the fly ash as a base material and hence D_{15b} for untreated fly ash as a base material is 0.28 mm.

5.3 FLY ASH TREATED WITH 6% LIME

5.3.1 Cylinder Dispersion Tests

Tests were carried out at various periods of curing, in both distilled and tap water. The test results are as given below:

(A) Two days curing

(i) Behaviour in distilled water

Two tests were conducted and results had shown that behaviour was similar to that of fly ash (untreated) in distilled water. The only difference being that time of collapse had increased from 5-7 minutes (in case of fly ash without lime) to 15-17 minutes (in case of fly ash treated with lime).

Thus fly ash treated with 6% lime after 2 days curing period exhibits Type N beaviour

(ii) Behaviour in tap water

Here again two tests were employed and it was found that exactly similar behaviour (Type N) occured in tap water. Time of collapse was still 15-17 minutes.

(B) Seven days curing

(i) Behaviour in distilled water

Here again except for the time of collapse, the observed behaviour was similar to that of fly ash (Type N) without lime. Time of collapse varied between 25-35 minutes.

(ii) Behaviour in tap water

Here also except for the time of collapse, the similar behaviour (Type N) was observed and the time of collapse of the sample was 40 - 60 minutes.

(C) Fourteen days curing

(i) Behaviour in distilled water

On the basis of 2 tests, it was found that behaviour of the 14 days cured sample of fly ash treated with lime in distilled water was similar to that of fly ash in distilled water (i.e. Type N). Time of collapse of the sample varied between 50 - 55 minutes.

(ii) Behaviour in tap water

Two tests were conducted and these have shown following results.

When the sample was gently lowered in the beaker containing tap water, there was no immediate erosion of the sample surface. The sample remained unaffected even after 3 days, except for a minor surface erosion near the bottom of the sample.

Accoridng to Atkinson (1990) fly ash treated with 6% lime after 14 days curing, exhibits Type C behaviour in tap water.

(D) Twenty one days curing

(i) Behaviour in distilled water

Two tests were conducted and it was found that in each test, sample remained unaffected and final water colour was slightly milky. Thus this shows that this sample too exhibits Type C behaviour in distilled water.

(ii) Behaviour in tap water

Two tests were conducted in tap water and in each test, behaviour similar to that in distilled water (Type C) was observed. The final water colour was also slightly milky in this case.

5.3.2 NEF Test for Treated Fly Ash as a Base Material

NEF tests were conducted on treated fly ash (i.e. fly ash treated with 6% lime and after 21 days storage at $16 \pm 3^{o}C$) by using two different types of filter material and following results were obtained.

(A) Filter material having D_{15} = 0.53 mm (gradation curve 3 of Fig. 5)

In order to check suitability of this filter material, three tests were conducted and the results are as given below:

Initial discharge under the normal head varied between $2.315 \times 10^{-2} - 2.598 \times 10^{-2}$ ml/sec.-cm^2 and water was dirty. Pressure

of 2.5 kg/cm^2 was applied for 20-23 minutes, water was still coming dirty for first 8 - 10 minutes and then it became clear.

Discharge measured under the normal head had varied between 1.400×10^{-2} - 1.559×10^{-2} ml/sec.-cm^2 and water was clear. Pressure of 2.5 kg/cm^2 was once again applied for 15 - 20 minutes and the colour of water during pressure application was clear. Discharge measured subsequently under the normal head varied between 1.231×10^{-2} - 1.314×10^{-2} ml/sec.-cm^2.

The final diameter of the hole had become 7 to 8.5 mm and erosion channels were formed on the bottom surface of base sample. Thus, these results indicate that this material (D_{15} = 0.53 mm) is an unsuccessful filter for treated fly ash as a base material.

(B) Filter material having D_{15} = 0.43 mm (gradation curve 2 of Fig. 5)

Three tests were employed by using this filter material and the results are as given below.

Initial discharge under the normal head had varied between 1.999×10^{-2} - 2.338×10^{-2} ml/sec.-cm^2; water was clear. Pressure of 2.5 kg/cm^2 was applied for 20 - 35 minutes and water was clear during pressure application. Subsequent discharge measured under the normal head varied between 1.314×10^{-2} - 1.443×10^{-2} ml/sec.-cm^2; water was still clear.

After conducting the test, it was found that the hole diameter had remained nearly same and erosion channels were found on the bottom of the base sample.

Above results indicate that this material (D_{15} = 0.43 mm) is a successful filter for treated fly ash as a base material.

<u>Filter boundry</u> (D_{15b}) <u>for treated fly ash</u>

As tests conducted with materials having D_{15} greater than 0.43 mm, were found unsuccessful, so D_{15b} of treated fly ash is 0.43 mm.

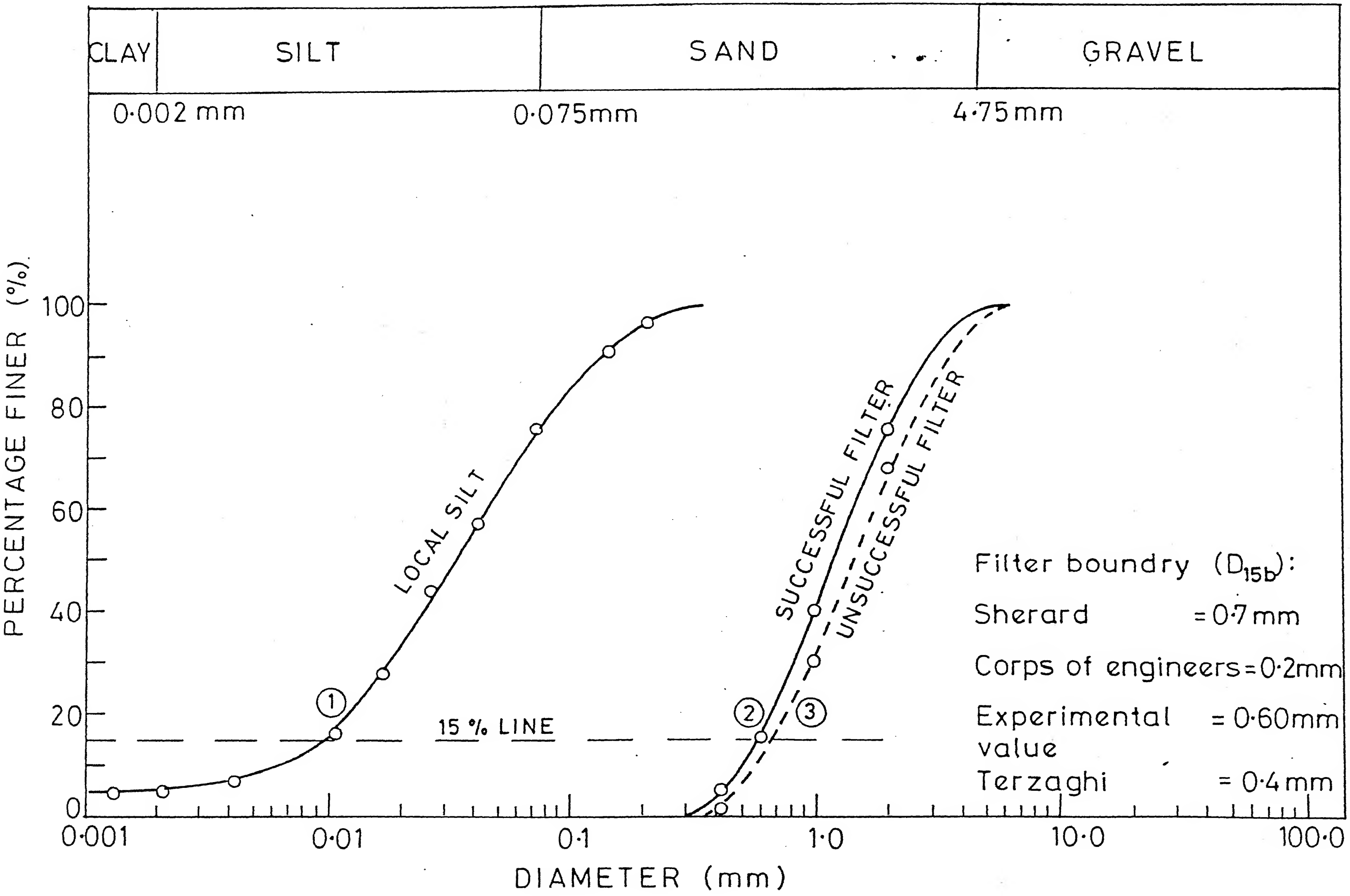
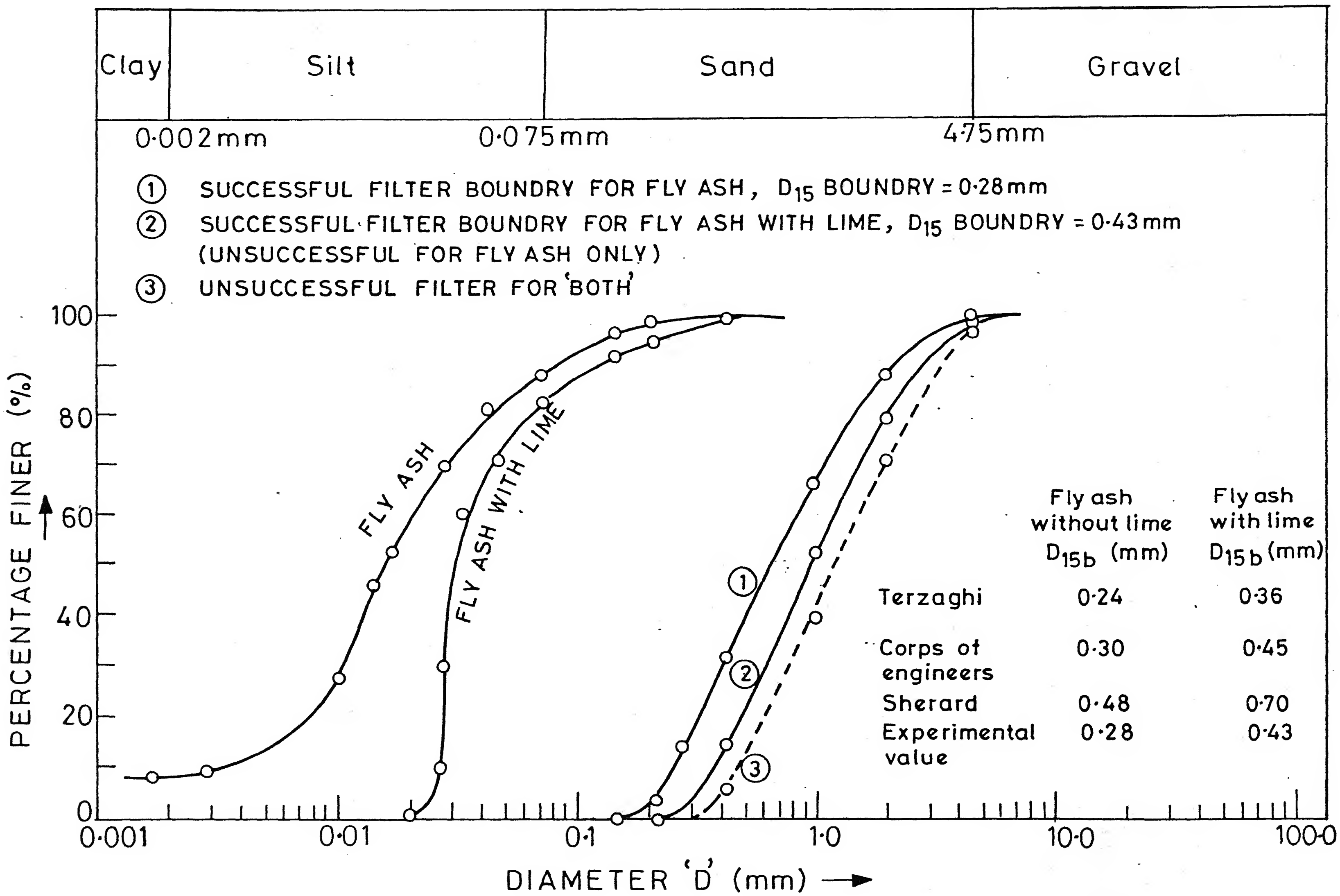


FIG.4 FILTER GRADATION CURVE FOR LOCAL SILT



FIG·5 FILTER BOUNDRY BY NEF TEST

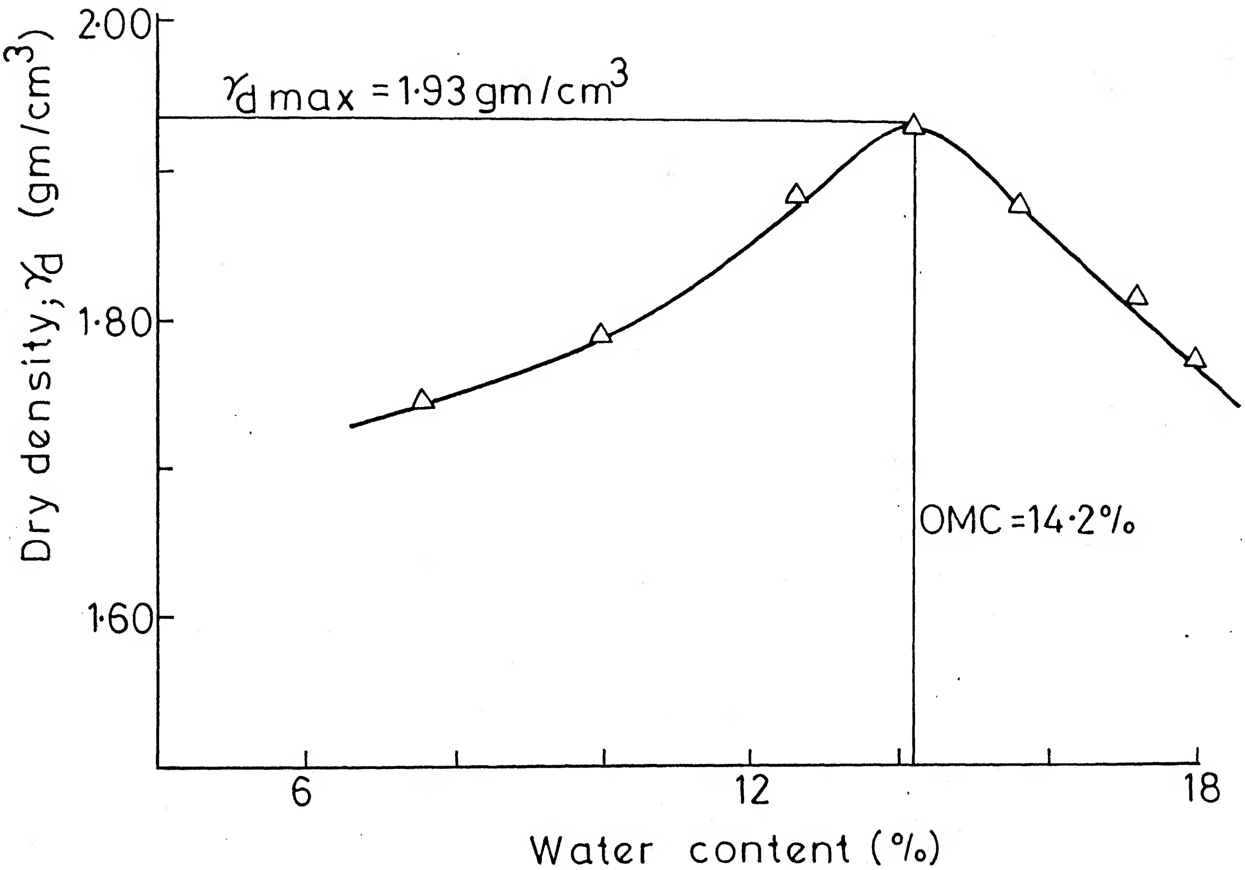
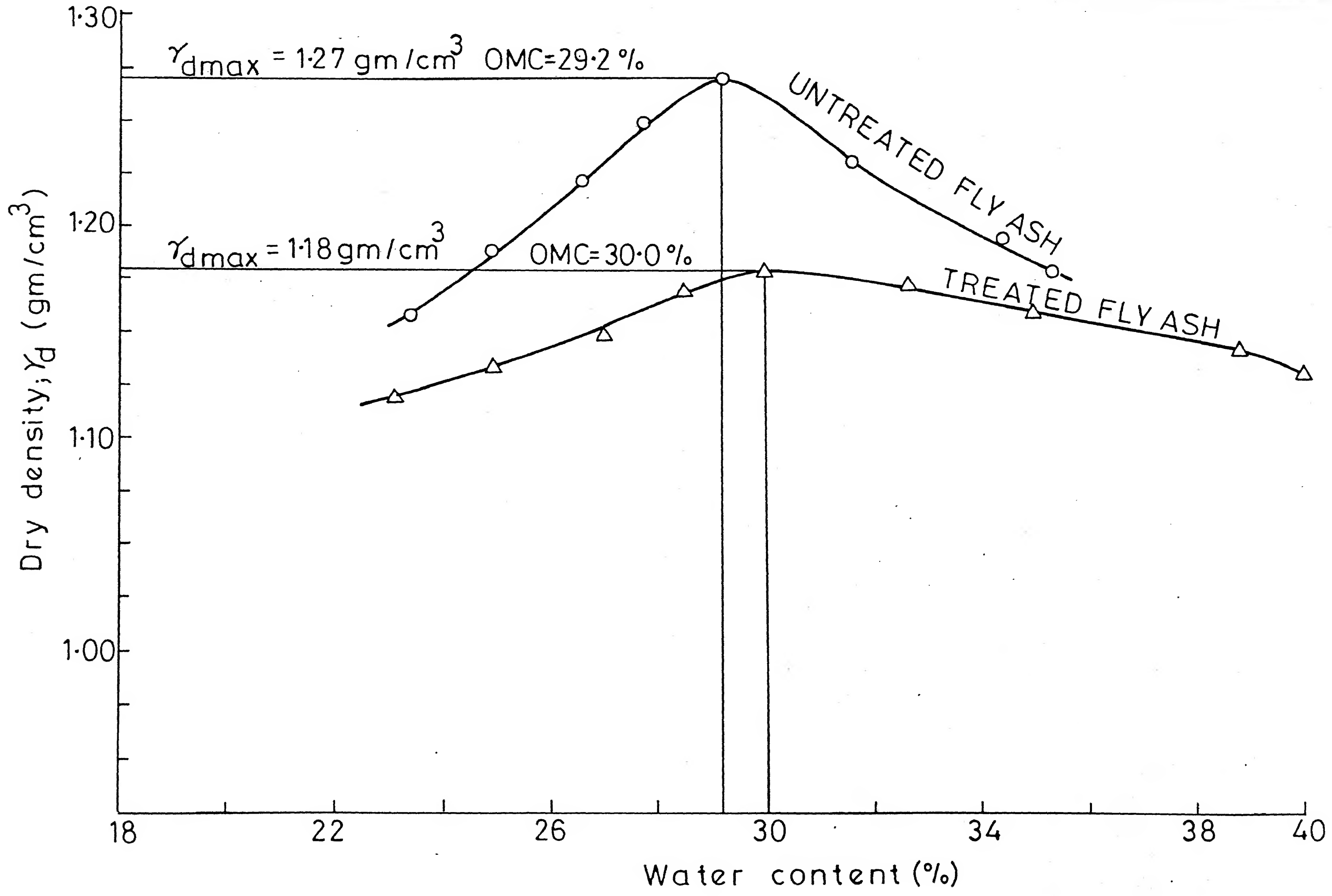


FIG. 6 COMPACTION CURVE FOR LOCAL SILT



FIG·7 COMPACTION CURVES FOR BOTH FLY ASH UNTREATED & TREATED WITH LIME

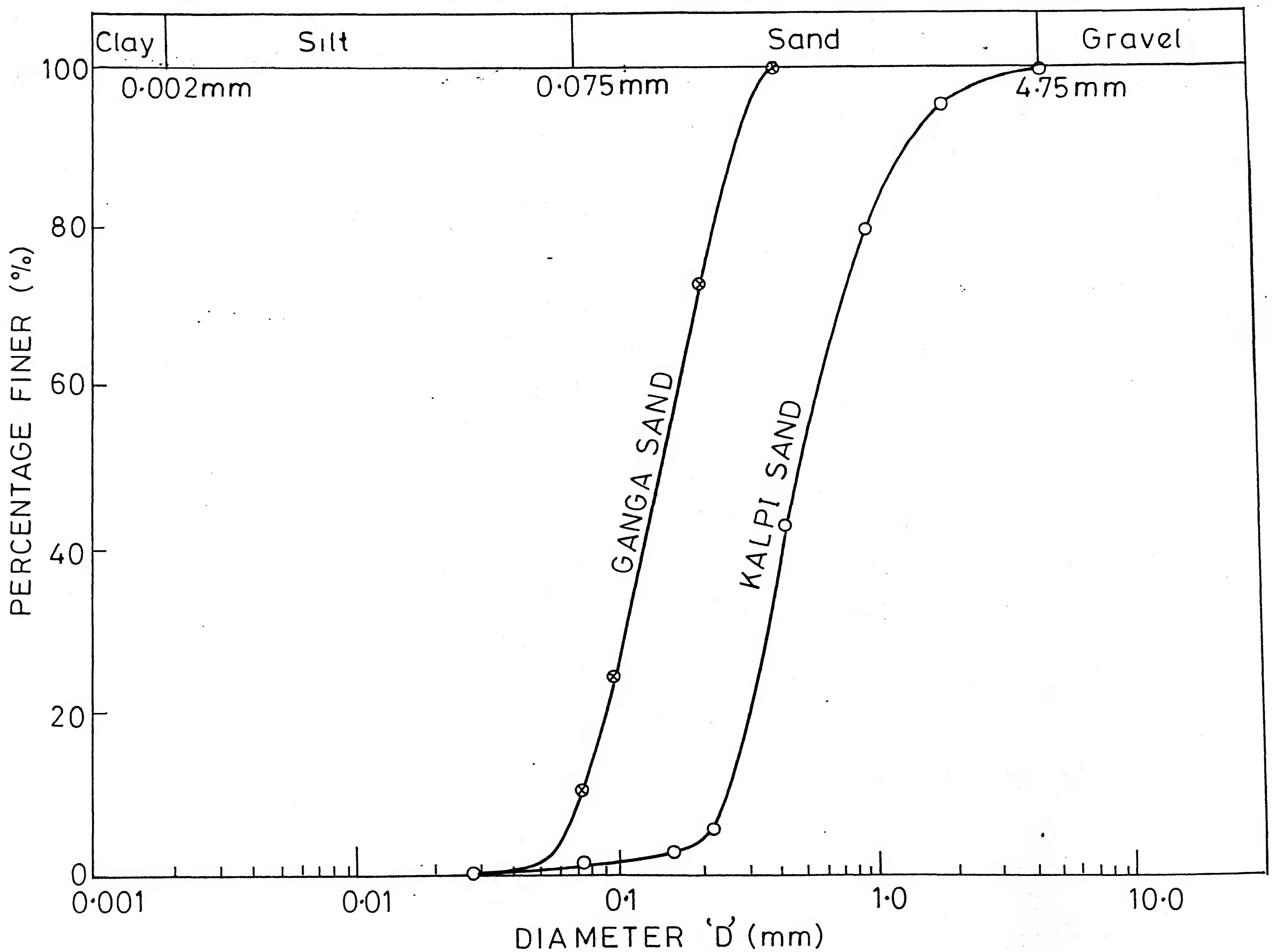


FIG.8 GRADATION CURVES OF GANGA SAND AND KALPI SAND

CHAPTER VI

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 DISCUSSION

6.1.1 Erosion Resistance of Local Silt & Fly Ash:

Results of the cylinder dispersion tests on local silt & fly ash are summarized in Table 1. The local silt behaved like what Atkinson et al. (1990) describe a soil with negative true cohesion. As soon as the consolidated sample had attained equilibrium after immersion in water (both distilled & tap) i.e. the effective stress had reduced to zero after the suction had dissipated; the particles of the soil started dislodging from the sample surface and the water in the beaker became so muddy after 35-42 minutes that the liquid had become opaque. Debris had settled at the bottom of the beaker. Even after 24 hours liquid was opaque and it was not possible to clearly see the sample, though a reduced cylindrical section of the sample could be felt with fingers. These observations would imply that the local silt exhibits dispersive behaviour as per cylinder dispersion test. According to the erosion behaviour classification proposed by Atkinson et al. (1990), local silt may classified as type D material. This behaviour agrees with the field observations on

TABLE 1: CYLINDER DISPERSION TEST RESULTS

Type of Soil	Collapse Time (minutes)		Observed shape of debris deposit		Final colour of water after 24 hrs.		Classification of of soils w.r.t. erodibility/ dispersibility	
	Tap water	Distilled water	Tap water	Distilled water	Tap water	Distilled water	Tap water	Distilled water
Local Silt	40-42*	35-37*	Muddy Suspension	Muddy Suspension	Muddy	Muddy	Type D	Type D
Fly Ash	5-7	5-7	Fig.3(b)	Fig.3(b)	Clear	Clear	Type N	Type N
Fly Ash treated with lime and curing period of								
(a) 2 days	13-15	11-14	Fig.3(b)	Fig.3(b)	Slightly milky	Slightly milky	Type N	Type N
(b) 7 days	40-60	25-35	Fig.3(b)	Fig.3(b)	-do-	-do-	Type N	Type N
(c) 14 days	Did not collapse	50-55	Unaffected sample	Fig.3(b)	-do-	-do-	Type C	Type N
(d) 21 days	Did not collapse	Did not collapse	Unaffected sample	Unaffected sample	-do-	-do-	Type C	Type C

* No sudden colapse but gradual dispersion of soil leading to debris formation at the bottom of the beaker.

embankment slopes of compacted local silt, subjected to rain water. Furthermore, such a compacted material which is brittle in nature, is likely to experience cracking in the field and if water is stored behind embankments of this material, concentrated leaks are likely to develop.

Fly ash (without any lime treatment) on the otherhand behaved like a practically non cohesive material. First of all untreated consolidated samples were quite difficult to handle during removal from consolidation tubes & immersion under the water. As soon as the sample was submerged in water (both distilled & tap), particles of fly ash started separating from the sample immediately. Cracks appeared at the bottom, propagated upwards & after 5-7 minutes the sample experienced instability under its own weight and collapsed. This behaviour is practically like that of a cohesionless sand except that the highly brittle behaviour of fly ash at very low stresses (Singh 1989), whereas induced cracking & instability of the sample. This difference in the behaviour could be seen in the shape of debris produced at the bottom of the beaker. While a sand sample would have produced a triangular form as shown by Atkinson et al. (1990), whereas the fly ash samples produced a small cylindrical stub in the centre surrounded by the over turned parts of the sample and horizontal debris deposit as shown in Fig. 3b. According to the erosion behaviour classification proposed by Atkinson et al. (1990), fly

ash may be classified as Type N (Non dispersive & cohesionless) material.

Treatment of the fly ash with lime was expected to impart positive true cohesion in the fly ash with curing time. As shown in Table 1, the collapse time of the sample in distilled water increased with curing time upto 14 days and the sample exhibited Type N behaviour. the behaviour in tap water was also similar to that in distilled water upto a curing time of 7 days. The 14 days sample in tap water and 21 days samples in both tap & distilled water, behaved like a material with positive true cohesion and the samples remained intact with clear surrounding water. These samples would be classified as Type C (Non dispersive & cohesive).

An unconfined compression test on a 21 days cured sample (and submerged in water for 3-4 days during cylinder dispersion test) gave a value of only 0.23 kg/cm^2, where as a 21 days cured at 25^oC compacted sample of treated fly ash gave a corresponding value of 4-5 Kg/cm^2. The curing during the test took place at a temperature of around 16 ± 3^oC, whereas for proper curing the minimum temperature required is 25^oC (Singh 1989). The cured samples even after 21 days had developed a hardened thin skin which broke off like a thin sheet when the sample was failed in unconfined test. The material inside the hardened skin was practically as soft as that of the samples before curing. These observations would suggest that proper gel formation has not taken place & full benefit of curing was not available. This may be the

reason for very low value of unconfined comprehensive strength (0.23 kg/cm^2 only), and also of the observed tendency for collapse on immersion in distilled water even after 14 days. However, as expected lime treatment had produced flocculation of fly ash particles as shown in the Fig. 5. Actually the increase in collapse time on immersion may be primarily due to flocculated nature of treated fly ash, along with a thin hardened skin. Properly cured treated fly ash at a temperature equal to or greater than $25^{0}C$, is expected to give a much enhanced resistance to erosion.

6.1.2 NEF Tests on Local Silt and Fly Ash:

Results of No Erosion filter tests results are summarized in Table 2. It will be noted that for a successful NEF test, the following conditions need to be met:

(i) Discharge under the normal head through the hole in base sample, decreases after the water is forced through the hole under high pressure.

(ii) The hole diameter does not change during the test.

(iii) After attaining the equilibrium condition, the water coming out of the filter is absolutely clear without any fine colloids in it.

(A) Local Silt:

On the basis of tests on different gradation of the filter materials, the D_{15b} (i.e. filter boundry) of the successful filter in case of local silt comes out to be 0.6 mm. Sherard & Dunnigan

(1989) suggest a value of 0.7 mm for this type of base soil. The values of D_{15} as recommended by Terzaghi and also by the US Corps of Engineers, are shown in Fig. 4, along with the experimentally determined value of D_{15b} in this study. Experimentally determined value is greater than the values according to Terzaghi & US Corps of Engineers criteria. The experimental setup and the test procedure adopted in this study thus affords a convenient method to design a successful filter for a dispersive soil, with likelyhood of cracking in compacted state.

(B) Fly Ash Without Lime:

As indicated earlier, this material is like a cohesionless soil and is likely to experience excessive erosion when subjected to concentrated leaks through it. Interestingly the D_{15b} = 0.28 mm of a successful NEF test compares quite favourably with a D_{15} =0.24 mm as recommended by Terzaghi. In comparison the D_{15b} = 0.6 mm for local silt is significantly greater than D_{15} = 0.4 mm according to Terzaghi's criterion. However, the US Corps of Engineers' value of D_{15} is much less than both Terzaghi & NEF as shown in the Fig. 5. Recommendation by Sherard & Dunnigam (1989) is also depicted in Fig. 5. It will be seen that Sherard's recommended D_{15b} = 0.48 mm, which is more than 0.28 mm as obtained from the NEF test in present investigation. While fraction finer than 75 micron of fly ash may place it in Sherard's group 1 along with other soils, it is to be noted that by its very nature, fly ash particles have absolutely no mutual attraction and when water

TABLE 2: NEF TEST RESULTS

Base Material	Filter Material D_{15} (mm)	Discharge under the Normal Head $ml/sec.-cm^2$		Colour of water discharged		Diameter of the Hole in the base sample (mm)		Test Result
		Initial	Final	*In the beginning	After pressure application	Initial	Final	
Local Silt	0.7	$2.338x10^{-2}$ $-2.923x10^{-2}$	$1.299x10^{-2}$ $-1.670x10^{-2}$	Turbid	Turbid	2.5	~ 4.0-5.0	Unsuccessful
	0.6	$2.338x10^{-2}$ $-2.598x10^{-2}$	$1.046x10^{-2}$ $-1.231x10^{-2}$	Turbid	Clear	2.5	~ 2.5	Successful
	0.3	$2.12x10^{-2}$ $-2.338x10^{-2}$	$0.974x10^{-2}$ $-1.057x10^{-2}$	Clear	Clear	2.5	~ 2.5	Successful
Untreated Fly Ash	0.53	$2.033x10^{-2}$ $-2.338x10^{-2}$	$1.559x10^{-2}$ $-1.670x10^{-2}$	Blackish	Blackish	5.0	~ 6.0-8.0	Unsuccessful
	0.43	$1.999x10^{-2}$ $-2.165x10^{-2}$	$1.314x10^{-2}$ $-1.461x10^{-2}$	Blackish	Blackish	5.0	~ 6.0-7.5	Unsuccessful
	0.28	$1.799x10^{-2}$ $-1.999x10^{-2}$	$1.063x10^{-2}$ $-1.169x10^{-2}$	Clear	Clear	5.0	~ 5.0	Successful
Treated Fly Ash	0.53	$2.315x10^{-2}$ $-2.598x10^{-2}$	$1.231x10^{-2}$ $-1.314x10^{-2}$	Blackish	Blackish	5.0	~ 7.0-8.5	Unsuccessful
	0.43	$1.999x10^{-2}$ $-2.338x10^{-2}$	$1.314x10^{-2}$ $-2.338x10^{-2}$	Clear	Clear	5.0	~ 5.0	Successful

* This colour of the water is noted under instance when pressure for the first time was applied.

flows through the central hole in the base sample, the fly ash particles disperse themselves throughly, as compared to the natural soils in which the dislodged particles are usually flocs (Vaughan and Soares 1982). It is for this reason that for a natural soil in compacted form in group 1 of Sherard & Dunnigan (1989), a coarser filter would be successful as compared to the case of fly ash which would need a finer filter. It would therefore seem that in case of fly ash the recommendations of Terzaghi for cohesionless soils may be equally applicable and the actual NEF test results for this material are not in agreement with the recommendations of Sherard & Dunnigan (1989) on the basis of fractions less than 75 micron sieve only. This difference in behaviour between natural cohesive compacted soils & compacted fly ash is primarily due to the cohesionless character of fly ash. While in case of compacted natural cohesive soils, water under pressure through the hole in a NEF test will dislodge flocs & not the individual soil particles, but in case of fly ash due to lack of any mutual attraction between particles, individual fines & not flocs of fly ash will be dislodged from the underside of the base sample, which would need a relative fine filter than that for the cohesive soils.

(C) Fly Ash with 6% Lime and Stored for 21 days before compaction

As seen from Table 2, in case of treated fly ash D_{15b} of successful filter is 0.43 mm as compare to 0.28 mm for untreated fly ash. This difference is clearly due to the flocculation

produced by lime treatment (Fig. 5). While Terzaghi & US Corps of Engineers' values 0.36 mm & 0.45 mm respectively are close to the NEF test results, recommendations by Sherard are much higher. Once again as in the case of untreated fly ash, the percentage fraction less than 75 micron basis of grouping soils is valid only for cohesive materials, which will produce flocs rather than individual particles as a result of concentrated leak. Since curing was not proper as discussed earlier, and the flocs of treated fly ash were not cemented toegher by the gel formation, action of high pressure water flow is likely to break up the flocs into finer particles, which would need a finer filter compare to one recommended by Sherard.

6.2 CONCLUSIONS

On the basis of the test results presented in tables 1 and 2 and as discussed above, the following conclusions may be drawn:

1. The experimental setup as designed and used in this study was found to be satisfactory to conduct NEF test on filter materials. This set up can now be used for designing filters in case of cracked cores of earth dams & embankments. In addition a detailed procedure for conducting NEF tests in this setup has been established.

2. Following Sherard and Dunnigam (1989), the NEF setup employed in this study is useful for designing filters in case of dams/embankments cores built with dispersive/erosive materials, which are very likely subjected to cracking.

3. Observed reduction in discharge through the filter after high pressure flow through the base material, confirms the findings of Sherard & Dunningan (1989) that a thin impervious layer is formed on the filter surface which acts as an impervious element.

4. In case of dispersive cohesive soils, the Sherard & Dunnigan (1989) recommendations can be adopted as guide lines. NEF test results for local silt which is dispersive & cohesive are in aggrement with Sherard's guidelines.

5. In case of fly ash (both treated & untreated) which is highly erosive & non cohesive, recommendations by Sherard & Dunngam (1989) will provide a coarser filter than that required, whereas the predictions by Terzaghi & US Corps of Engineers, are in aggrement with the requirements of a successful filter as obtained from a NEF Test.

6. For a successful NEF test it is important that in addition to the requirements of decrease in discharge & no change in the diameter of the hole, the colour of water must be absolutely clear after attaining the equilibrium. This conclusion is in agreement with that of Sherard & Dunnigam (1989) and it is reemphasized because in literature (Pinto et al. 1990) even with muddy water after attaining the equilibrium, the NEF test has been adjudged as successful simply on the basis of no change in hole diameter only.

7. The cylinder dispersion test recommended by Atkinson et al. (1990), is a useful test procedure to classify the materials on the basis of their erodibility/dispersibility characteristics.

6.3 RECOMMENDATIONS

1. The test setup used here should be improved in terms of a constant high pressure water supply system.
2. The cohesive – non cohesive range of the soils should be further investigated with NEF tests, to refine the validity of recommendations by Sherard & Dunningam (1989) on the basis of less than 75 micron fractions only.
3. While Sherard & Dunningan (1989) and Tarzaghi recommended D_{15} only as the important parameter in filter design, it is suggested that with the same D_{15} (say of a successful filter) effect of gradation curve of the filter material on its performance should be investigated.

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